THEORETICAL & APPLIED MECHANICS LETTERS **4**, 052001 (2014)

Magnetohydrodynamic process in solar activity

Jingxiu Wang,[a)] Jie Jiang[b)]
National Astronomical Observatories, Key Lab of Solar Activity,
Chinese Academy of Sciences, Beijing 100012, China

(Received 5 September 2014; accepted 8 September 2014)

Abstract Magnetohydrodynamics is one of the major disciplines in solar physics. Vigorous magnetohydrodynamic process is taking place in the solar convection zone and atmosphere. It controls the generating and structuring of the solar magnetic fields, causes the accumulation of magnetic non-potential energy in the solar atmosphere and triggers the explosive magnetic energy release, manifested as violent solar flares and coronal mass ejections. Nowadays detailed observations in solar astrophysics from space and on the ground urge a great need for the studies of magnetohydrodynamics and plasma physics to achieve better understanding of the mechanism or mechanisms of solar activity. On the other hand, the spectacular solar activity always serves as a great laboratory of magnetohydrodynamics. In this article, we reviewed a few key unresolved problems in solar activity studies and discussed the relevant issues in solar magnetohydrodynamics.
 [doi:10.1063/2.1405201]

Keywords solar magnetic field, solar activity, magnetohydrodynamics, numerical simulation

I. INTRODUCTION

Magnetohydrodynamics (MHD) is a branch of physics dealing with the behavior and effect of magnetic fields in moving plasmas. The early development of MHD theories, in fact, was tied with the problem how the magnetic fields in the Sun and stars are generated and maintained.[1] Solar MHD is one of the major disciplines in solar physics and provides a frame work in understanding the dynamics and activity in solar magnetized atmosphere.[2] MHD process mainly takes place in the solar convection zone and atmosphere in controlling the generation, structurization, and energy transformation in solar magnetism and activity.

For the near future the solar activity studies are aimed to reach the following goals: to determine how the Sun generates the magnetic field that varies cyclically and controls the dynamics and activity in the Sun and heliosphere, to understand accurately on how the magnetic energy is accumulated in the solar atmosphere and explosively released in the form of violent flares and coronal mass ejections (CMEs), and to find how the solar magnetic field couples the photosphere, chromosphere and corona, creating the solar wind and causing the unusual heating of chromosphere and corona. By achieving the above scientific goals, solar scientific community will be

a)Corresponding author. Email: wangjx@nao.cas.cn.
b)Email: jiejiang@nao.cas.cn.

able to found the physical basis for predicting the disastrous space weather.

Solar physics is an observational science. In recent years, unprecedented high tempo-spatial resolution observations of the solar atmosphere have been made, e.g., the extreme ultraviolet (EUV) spectra by the Hinode Extreme Ultraviolet Imaging Spectrometer (EIS)[3] and the multi-wavlength images by the Solar Dynamics Observatory (SDO) Atmosphere Imaging Assembly (AIA).[4] For the first time, solar vector magnetic field in the solar photosphere has been mapped from space with advanced Stokes polarimetry technique for solar active and quiet regions by Solar Optical Telescope/Stokes Polarimeter,[5] and for the full disc by the Helioseismic and Magnetic Imager (HMI) of SDO.[6] However, there are still a few missing links in establishing the solid grand of physical understanding on solar MHD process. For instance, to understand the origin of solar magnetic field, i.e., the solar dynamo process, we need to measure the mass flow in the convection zone and at the tachocline, and to explore the physical nature of magnetic diffusion. To identify the triggering mechanism(s) and tempo-spatial structures of flare/CME initiation is a key task for activity studies and space weather forecast. Very recently, the Interface Region Imaging Spectrograph (IRIS) was launched and started to create simultaneous spectra and images mainly in the solar chromosphere and transition region, the interface region between photosphere and corona.[7] IRIS aims at advancing our understanding of the mass and energy flow from photosphere through this interface region to corona.

On the other hand, solar activity studies now appeal for the scientific input from MHD and plasma physics. Not only because the recent observations have been able to provide detailed specifications for MHD simulation and plasma laboratory experience, but also due to the limitation of the current observations in exploring the temporal and spatial scales of physical interaction, the three dimension MHD simulations would provide a powerful and imperative tool to test our knowledge gained from observations and examine the existing models and theories. IRIS investigation does include numerical modeling component based on advanced radiative-MHD codes.[7]

In this article we will focus on the following issues: the current knowledge about solar dynamo and solar activity, and the need for MHD theoretical and numerical studies.

II. SOLAR DYNAMO

The process behind solar magnetic activities is believed to be a hydromagnetic dynamo operating in the solar interior. The dynamo process is based on the nonlinear interactions between the velocity field and the magnetic field of the solar plasma. The nonlinear interactions are described by the MHD equations. In the solar cycle context, a physical dynamo model of the solar large-scale magnetic field is expected to reproduce the observed features of solar cycle. Except for the solar cyclic activities, there also have rapidly varying magnetic structures on the smallest observed scales of order 100 km. There would appear more magnetic energy on even smaller scales that are beyond current resolution limits.[8] They are suggested to be the results of a small-scale dynamo.

The main challenge of the direct numerical simulation of all the MHD equations is to model the convection properly. The solar convection zone is highly stratified, with quantities like density and pressure varying by several orders of magnitude from the bottom to the top. The magnetoconvection has a dynamic range of about 10^8 orders of magnitude or more, and magnetic Reynolds numbers can reach 10^8–10^{10}.[9] It is often assumed that the large-scale dynamo operates in a kinematic regime such that fields are passively amplified and transported by the large-scale flows. The large-scale flows include the differential rotation (Ω) and the meridional flow.

The kinematic theory for the large-scale fields basically has to be of the nature of a mean field theory.[10] In contrast to the magnetic induction equation, there is an additional term, i.e., the mean electromotive force for the equation that the mean magnetic field obeys. Parker[11] proposed that the sunspot cycle is produced by the oscillation between toroidal and poloidal components of the solar magnetic field. The stretching of the poloidal field by differential rotation produces the toroidal field. This is the so-called Ω-effect.

The source term for the poloidal field under the mean-field dynamo framework is the α-term. The helical turbulence acting on the toroidal field can gives rise to the poloidal field. This is known as the α-effect. One of the most remarkable properties of the $\alpha\Omega$ dynamo equations is that they support travelling wave solutions, which was the origin of the observed equatorward drift of sunspot emergences in the course of the cycle.

Another mechanism for the generation of the poloidal field is based on the observations of solar surface magnetic field. The bipolar sunspots appear on the solar surface with tilts. When a tilted bipolar sunspot decays, the two polarities preferentially diffuse around in slightly different latitudes. This gives rise to an axial dipole moment. Since the bipolar sunspots form from the toroidal field, the net effect of this process is that the toroidal field gets converted into the poloidal field. This mechanism of the poloidal field generation was developed by Babcock[12] and Leighton.[13] Hence it is called as the Babcock–Leighton (BL) process. It is a bit like α-effect in mean-field theory. In both cases the Coriolis force is the agent imparting a twist on a magnetic field, but on different spatial scales.

The BL dynamo models have been proved to be the most promising one by the studies in the past few years. The theoretical model is reasonably successful in explaining the behaviors of both sunspots and the poloidal field at the surface, as well as the phase relationship between them. The most advantage of the models is that the BL mechanism is directly observable. This can form the basis of solar cycle prediction schemes assimilating surface data into BL dynamo models,[14] and provide valuable information regarding the origin of observed cycle fluctuations, e.g., the grand solar minima.[15] Cycle 23 had a deep minimum (Fig. 1), which was suggested to be the cause of the current weak cycle 24.[16] The unusual cases that big sunspots with high tilt angles emerge near the equator have significant effects on the surface poloidal field generation.[16] This stochastic mechanism is most probably responsible for the occurrences of the solar grand minima.

Small-scale dynamo action has been proposed to account for the ubiquitous small-scale field.[17] The MHD equations must be solved in their fully compressible regime and with proper treatment of ionization and radiative transfer. Moreover, the spatial resolution must be high enough to capture detailed structures with a typical length scale of $\leqslant 10^3$ km. This is accessible to local simulations of a small portion of the convective envelope. The best understood classes of small-scale dynamos are isotropic, homogeneous, incompressible flows with large magnetic Prandtl numbers. But for the Sun, it is very small (in order of 10^{-7}). For this case small-scale dynamos tend to generate intermittent magnetic fields on scales much smaller than the typical scale of the velocity field.

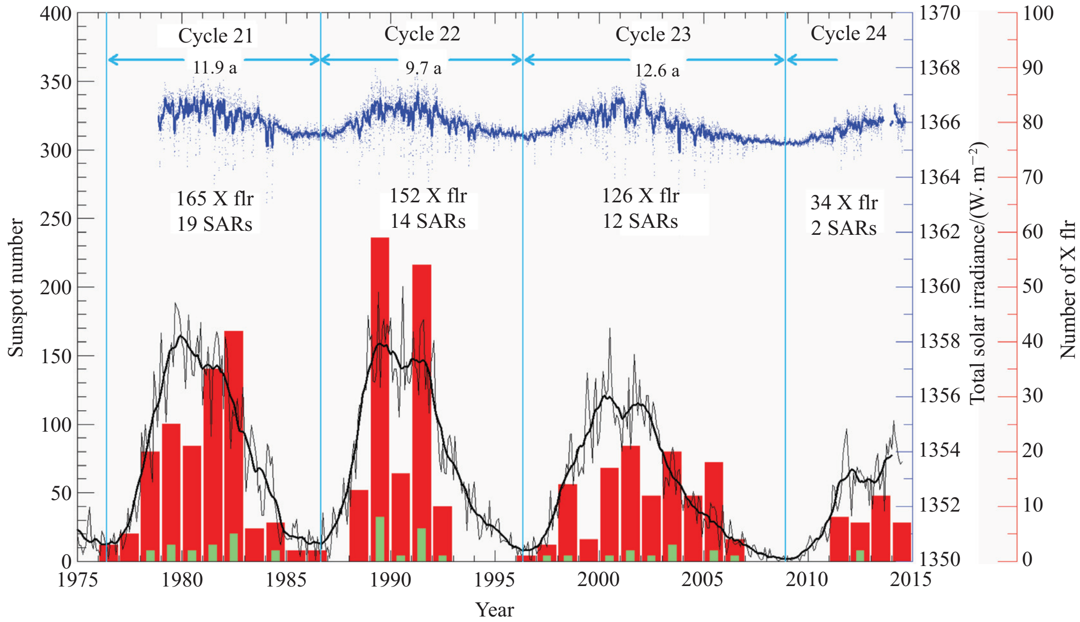

Fig. 1. Sunspot numbers since Cycle 21 are shown by black curves, total solar irradiance since 1978 is shown by blue curves, X class X-ray flares and super-active regions are displayed by histograms in red and green colors (courtesy Anqin Chen). In an interval from 2007 to 2009 the sunspot number dropped to the minimum level in the last 100 years and the total solar irradiance showed very low level too. For the current cycle, either the sunspot number, or the X class flare and super-active regions on the Sun are much less than the previous cycles. The grand minima and on-going mini-maximum present a challenge to solar dynamo studies.

III. SOLAR ACTIVITY

Solar activity involves an explosive release of magnetic energy that was previously stored in highly stressed solar magnetic field. Two types of the most violent activity are solar flares characterized by the tremendously enhanced electromagnetic radiation from a localized solar area and coronal mass ejections (CMEs) characterized by the impetuous ejection of huge amount magnetized plasma from the solar corona to interplanetary space.

Solar flare was first detected from the Sun in 1859 and CME, first observed in 1971. Extensive studies on solar activity have been carried out since 1930s. Many concepts with connection to MHD were first born in solar activity studies, e.g., magnetic reconnection, which is a means of rapid conversion of magnetic energy into heat and kinetic energy in plasma, was proposed to interpret flare phenomenon 70 years ago.[18] We now have gained some basic understanding on magnetic energy storage in the solar atmosphere and been aware of the role of magnetic helicity (a measure of topology complexity) in magnetic explosion.[19] The 3D topology skeleton in solar vector magnetic field, i.e., the magnetic null, spine, and fan surface, which are crucial for magnetic reconnection to occur, has been reconstructed.[20]

In the last decade, too much has been changed in solar activity studies. Data were acquired at a thousand-fold increasing rate. We are now able to achieve full-disc coverage of observations of our star with multi-wavelength images and polarization measurements.

A. Overall magnetic connectivity in solar atmosphere

The full-disc coverage of solar atmosphere images at UV, EUV, and X-ray wavebands and vector magnetograms enable us to be aware that solar active regions, coronal holes and quiet regions are ultimately connected by magnetic field. Magnetic connectivity in the solar atmosphere is rather global consisting of very complex topology structures. Flares and CMEs are no longer considered as two separate phenomena but thought as manifestations of a same physical process at different special environments and scales. Furthermore, a flare/CME event often involves multiple bipolar-regions which are in vigorous interaction, forming a complicated topology skeleton in which magnetic reconnection takes place. SDO/EUV Variability Experiment (EVE) observations have discovered the late-phase flaring,[21] which is likely to be a sympathetic flaring of nearby connected large-scale loops as described earlier.[22] In this sense we may claim that solar activity is the magnetic explosion in a complicated MHD system. The so-called standard flare model does represent some key ingredient of the flare scenario but tells only a part of a fantastic story. Flux rope which has helical magnetic lines of force along its long magnetic axis has been so commonly identified (or envisioned) in magnetic emerging flux regions, in activated filament structures and in flaring EUV coronal loops.[23] Various morphologies of magnetic reconnection between interacted magnetic fields are reported based on SDO/AIA observations (see Ref. 24). Torus instability of flux rope as a current channel has been suggested to play a key role in flare/CME onset.[25]

Often we are able to identify that active regions are clustered (see an example in Fig. 2). Adopting the common vision that the bright EUV loop structures trace the magnetic lines of force, we find that the two active regions (ARs) are connected by AR-connecting loops with an emerging flux rope underneath. The magnetic environment matches very well the magnetic skeleton derived in an MHD investigation for a case of quadrupole topology.[26] It has been demonstrated that ideal MHD catastrophe and the torus instability of current channel occurred, which specified the onset condition of solar eruption. Observations show that the AR cluster is quite common, in which many flare/CMEs took place. For this complicated magnetic configuration, MHD simulations are inevitably required to elucidate the mechanism(s) of solar explosion.

B. Exploring at the scale of physical interaction

While in one respect the magnetic field in solar atmosphere is globally connected; on the other hand, the physical interaction operated in solar activity takes place at very fine scale, e.g., scale of photo free path ($\sim$ 100 km in the solar photosphere). It is well-known that if the observed magnetic field has internal fine structure, i.e., only a fraction of f in the observed area was truly occupied by magnetic field, then the true magnetic energy density would be $B^2/(2\mu f)$. B is the observed field strength. The true magnetic energy density in the field is much larger than that was observed, provided $f \ll 1$.

First, nowadays solar observations are still biased by insufficient temporal, spatial, spectral resolutions and polarization sensitivity, so that the true physics picture of the magnetic annihilation and instability that result in the observed solar magnetic explosion is still beyond our grasp.

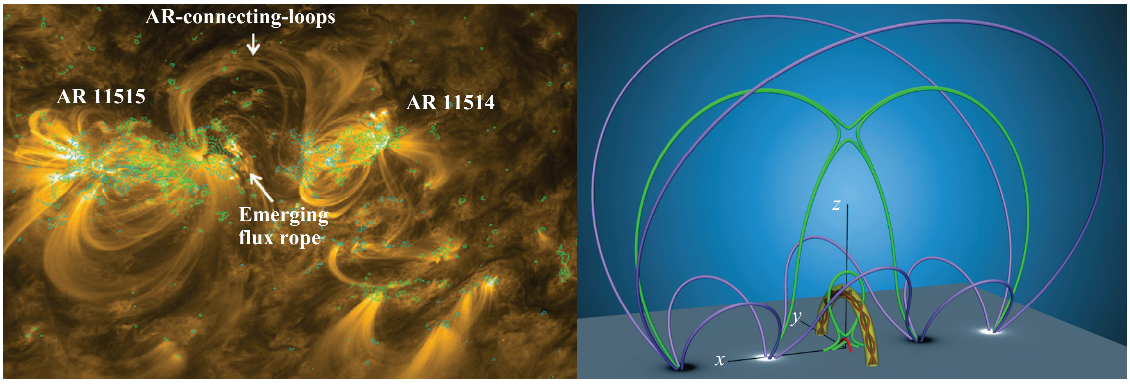

Fig. 2. SDO/AIA 17.1 nm image superposed by HMI iso-flux density contours at ±100 G, ±500 G, ±1 000 G, ±1 500 G (1 G = 10^{-4} T), showing overall magnetic connectivity with green (blue) contour for positive (negative) polarity (left panel). There is a flux rope in the form of new emerging flux region underneath the AR-connecting loops. Magnetic skeleton of a quadrupole magnetic configuration (right panel), in which a current channel is represented by transparent iso-current surface[26] (courtesy Bernhard Kliem). Green lines represent the topology skeleton, purple lines are for magnetic lines of force, and bottom image shows the quadrupole magnetic field.

Moreover, many types of micro-activity events, e.g., nano- and micro-flares, mini-filament eruptions and mini-CMEs, micro-spicules and bright points, are believed to play very key roles in the chromospheric and coronal heating, and plasma acceleration in solar wind. And, the whole hierarchic activity in solar atmosphere may likely to be coupled. In this sense, the micro-activity may serve as a trigger for AR-scale flares and more global-scale CMEs. Solar astronomers now are making solid progress step-by-step in access of physical interacting scale.

The New Solar Telescope (NST) of the Big Bear Solar Observatory, the largest solar telescope, which has 1.6 m aperture, has clearly observed the signature of magnetic flux emergence and followed flux cancellation with very high spatial (0.11$''$ at 705.7 nm, 1$''\approx$ 725 km on solar surface) and temporal (15 s) resolution in the photosphere.[27] The high resolution NST data on bright points in the photosphere are discussed and new ideas are proposed based on observations that a turbulent regime of super-diffusivity dominates in the quiet Sun;[28] there are local dynamos operating near the solar surface. Important hints were observed for coronal heating by the near infrared observations of NST. There were upward injections of hot plasma that excite the ultrafine loops from the photosphere to the base of the corona and the ejecta have their individual footpoints in the intergranular lanes between the solar ubiquitous, convectively driven granules.[29]

Experiences of space observations (e.g., Hinode/SOT) and ground-based observations, such as the Interferometric Bidimensional Spectrometer (IBIS)[30] and the Crisp Imaging Spectropolarimeter (CRISP)[31] at the 1 m Swedish Solar Telescope have educated us that to properly grasp the magnetism, dynamics, and fine-scale structuring in solar atmosphere future facilities should be able to observe both spectra and images at high spatial resolution ($< 0.3''$), temporal resolution (about a few seconds) and high polarization sensitivity (a few times of 10^{-4}) for a sizable fields of view (no less than 100$''$) and an enough temperature range from the photosphere to corona.

C. A need for radiative MHD simulation

In recent years, 3D radiative-MHD numerical simulations (RMHD) have been developed and applied by many solar research groups to improve our physical understanding about solar structure and activity. By RMHD it means that radiation transfer has been involved in the energy process in the general MHD equations in some ways that are treatable. In solar and general astrophysics, electromagnetic radiation is almost the only way to probe the physical properties of observed objects, therefore to have an elaborate theoretical tool in radiative transfer is crucial to interpret observed spectra and images with physical terms. The results of RMHD simulation enable a direct comparison between the results of numerical modeling and the observed spectra and images. Usually the synthetic diagnostics from numerical models are used to examine which if any of the assumptions in interpreting the observing data need to be relaxed and/or any interpretation is more plausible.

As an example, the RMHD simulation in the photosphere (with the MURaM code, MPS/University of Chicago Radiative MHD) has provided a way to obtain the information of 3D magnetic field structure from the convection zone to the top of photosphere which are not accessible to current observations in either resolving scale or the plasma domain, thus to help with elucidating the physics underlying the observed phenomena.[32] The importance of ambipolar diffusion and Hall currents for high-resolution photospheric simulation is investigated.[33] The RHMD simulations have been used to test observational diagnostics and the physical understanding of observed phenomena. An RMHD simulation covering the spans from the upper layer of the convective zone up to the low corona has been used to examine the temperature determination of coronal plasma based on the space observations with the Extreme ultraviolet Imaging Spectrograph (EIS) on board of Hinode and SDO/AIA.

The great advances in computational infrastructure and algorithms have revolutionized the state-of-the-art of numerical simulations which is playing a decisive role in interpreting observations. The newly opening facility of IRIS not only has unprecedented spatial, temporal and spectral resolution in observations but also includes an advanced RMHD simulation component to enable full forward-modeling of the plasma domain from the top of the convective envelope to the low corona.[7] This presents a new tendency for the future space-borne and ground-based projects.

This work was supported by the National Natural Science Foundations of China (11173033, 11221063, 2011CB811401, 11221063, and 11373004) and the Knowledge Innovation Program of the CAS (KJCX2-EW-T07).

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